POLY-SCIENTIFIC

DIVISION OF LITTON INDUSTRIES

POLY-SCIENTIFIC DIVISION OF LITTON SYSTEMS, INC. 1213 NORTH MAIN STREET BLACKSBURG, VIRGINIA 24060

TELEPHONE (703) 552-3011 TWX 710-875-3692

THE SYNERGISTIC EFFECTS OF SLIP RING-BRUSH DESIGN AND MATERIALS

Norris E. Lewis, Stephen R. Cole and E. W. Glossbrenner
Poly-Scientific Division
Litton Systems, Inc.
1213 North Main Street
Blacksburg, Virginia 24060

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16. Abstract

This program has involved the design, fabrication and subsequent testing of four power slip rings for synchronous orbit application. Environmental and instrumentation systems necessary for monitoring electrical noise, friction and brush wear in air and at less than 5×10^{-8} torr have been employed.

Composite brushes consisting of silver-molybdenum disulfide-graphite and silver-niobium diselenide-graphite have been employed on rings of coin silver and rhodium plate. These four contact combinations have been tested during an ambient condition run-in at 150 RPM and a humidity sequence at 0.1 RPM. Two years of vacuum testing totaling 3.45×10^6 cm. of ring travel have been completed at 0.1 RPM and a current density of 15.3 A/cm^2.

Electrical noise, friction and wear data generated during the test period along with post test analysis data have been presented.

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PREFACE

This program involved the design, fabrication and subsequent testing of four power slip rings for synchronous orbit application. Frequent and simultaneous recording of friction, wear and electrical noise enabled the synergistic effects of contact materials and slip ring-brush design to be studied.

The four ring and brush material combinations evaluated are as follows:

(A) Poly-Scientific Ag-MoS_2-C brushes vs rings of rhodium plate over nickel plate on a brass substrate (Combination A).

(B) Poly-Scientific Ag-MoS_2-C brushes vs coin silver (Silver-10% copper) rings (Combination B).

(C) Poly-Scientific Ag-$NbSe_2$-C brushes vs rings of rhodium plate over nickel plate on a brass substrate (Combination C).

(D) Poly-Scientific Ag-$NbSe_2$-C brushes vs coin silver rings (Combination D).

These four contact combinations have been tested under the following conditions:

1. Run-in at 150 RPM for 10 hours under ambient condition.
2. A five day humidity sequence at 0.1 RPM.
3. Two years of vacuum operation ($<5 \times 10^{-8}$ torr) at 0.1 RPM.

The results of the run-in, humidity and first nineteen months of vacuum operation have been previously reported [1-2]. This report contains data from the two years of vacuum testing and results of the post test analysis. The conclusions drawn after completion of this work are as follows:

<u>Electrical Noise</u>

1. Brushes lubricated with MoS_2 yielded lower noise values than those lubricated with $NbSe_2$.

2. The Ag-MoS_2-C/Rh and Ag-MoS_2-C/Ag combinations have given nearly equivalent noise performance beyond 1000 hours of vacuum operation.
3. Of the four materials combinations evaluated, low noise performance appears to be more closely related to the brush lubricant than the ring material.
4. The high noise on Combination C is related to the resistive film that formed between the negative brushes and rings.

Friction

1. There appeared to be no difference in friction coefficient for the three combinations remaining in operation at the end of the test. (Combinations A, B and C).
2. Friction coefficients were lower in vacuum than air for MoS_2 and $NbSe_2$ lubricants.

Wear

1. The Ag-$NbSe_2$-C/Rh and Ag-MoS_2-C/Ag combinations were wearing at the highest rates of the three combinations remaining in operation.
2. The high wear rate of Ag-$NbSe_2$-C/Rh is related to bridge formation on the rings which grooved some brush faces. The excessive bridge formation and arc damage was most likely related to the high resistance film formed on this combination.
3. The Ag-MoS_2-C/Rh combination exhibited little or no wear beyond 1000 hours of vacuum operation.
4. It appears that wear rate is the result of combination performance rather than a particular ring or brush material.
5. The wear rates for the neutral brushes on all combinations were not significantly different than those brushes with positive and negative polarity.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE SYNERGISTIC EFFECTS OF SLIP RING-BRUSH DESIGN AND MATERIALS

BY

N.E. LEWIS, S.R. COLE
AND
E.W. GLOSSBRENNER
POLY-SCIENTIFIC DIVISION
LITTON SYSTEMS, INC.

I. INTRODUCTION

This is the final report dealing with power slip ring contacts tested for low speed, high current transfer in a high vacuum environment of long term space usage. Earlier reports dealt with the atmospheric and vacuum test results of power slip rings and brushes under conditions simulating those anticipated for solar arrays on synchronous satellites and space probes.[1-2] The principal feature of these tests was the simultaneous recording of friction, wear, and noise at a very slow rotational speed.

The data presented represents the equivalent of 160 years of rotation of geosynchronous satellites. This paper presents data extending earlier results by a factor of 4 and correlates the post-test analysis with the behavior seen.

The results observed should be directly applicable to a wide variety of sliding contact applications in high vacuum both in space and other vacuum uses of slip rings.

II. EXPERIMENTAL

Four six circuit fixtures representing four materials combinations were operated over a two year period at a current density of 15.3 A/cm^2. Operating conditions were ambient temperature, a pressure of less than 5×10^{-8} torr and a ring speed of 0.1 RPM.

Silver graphite composite brushes utilizing equal volume fractions of MoS_2 or $NbSe_2$ as lubricants were employed with rings of coin silver and rhodium plate. Future reference to the four brush and ring combinations will be as follows:

Combination A: $Ag\text{-}MoS_2\text{-}C$ brushes on Rh rings;
Combination B: $Ag\text{-}MoS_2\text{-}C$ brushes on Ag rings;
Combination C: $Ag\text{-}NbSe_2\text{-}C$ brushes on Rh rings;
Combination D: $Ag\text{-}NbSe_2\text{-}C$ brushes on Ag rings.

The fixture design, electrical circuitry, description of system hardware and ring and brush material properties were previously reported.[1]

Post test analysis consisted of visual observations, metallographic sectioning of bridges and wear debris, and preparation of scanning electron micrographs (SEM) combined with energy dispersive X-ray analysis (EDAX) of selected brush faces. Ring and brush contact resistance measurements were made using a modified four probe apparatus.

III. RESULTS

A. Data

Friction and wear data were taken from four brushes on each fixture representing the following: an inductively loaded brush of negative polarity, resistively loaded brushes of positive and negative polarity and a neutral brush. Electrical noise data were taken from all six circuits of each fixture. A neutral brush on the sixth ring of each fixture allowed a positive and negative noise reading to be measured.

Friction, electrical noise and wear data generated during the two-year period have been presented in Figure 1. The friction and wear data represent averages of the four brushes equipped with transducers on each fixture. The noise data are averages of all six circuits. All data were averaged with respect to time to minimize the number of entries.

Throughout the first year a consistently higher coefficient of friction was observed for those brushes lubricated with $NbSe_2$ than those lubricated with MoS_2. After this period, the two approached a level of 0.25.

The highest wear rates occurred after 3000 hours of operation and were observed for Combinations B and C. The highest total wear was observed on Combination B (Figure 2). The data for Combination D represents only ten months of operation. Rotary motion feedthrough failure prevented data collection beyond this point.

The non parametric Mann Whitney U and Wilcoxan signed - rank test statistics were employed to compare the means of the electrical noise data. Several comparisons were made and these have been tabulated in Table I. Of those means compared the most

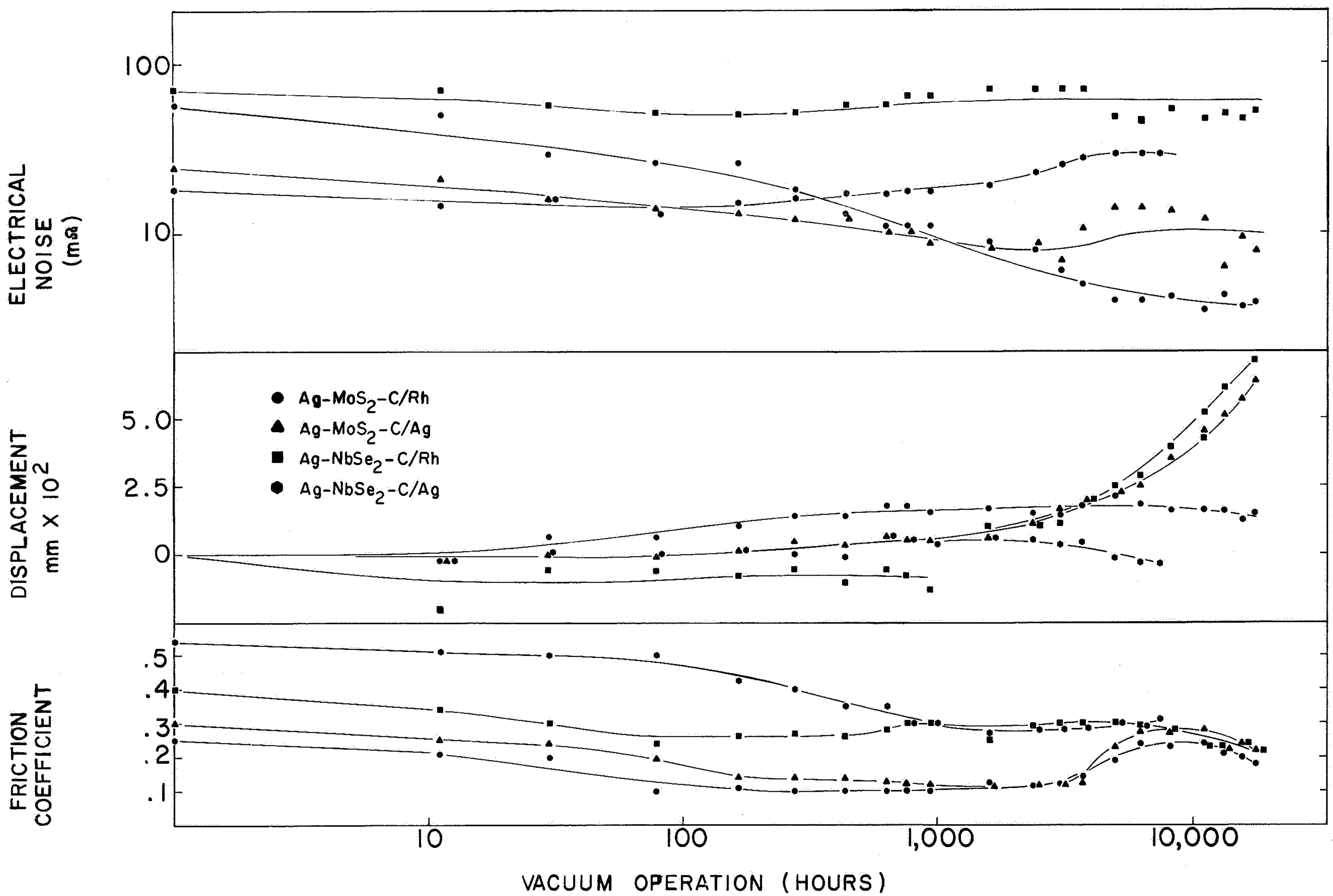


FIGURE I. ELECTRICAL NOISE, FRICTION AND WEAR DURING VACUUM OPERATION

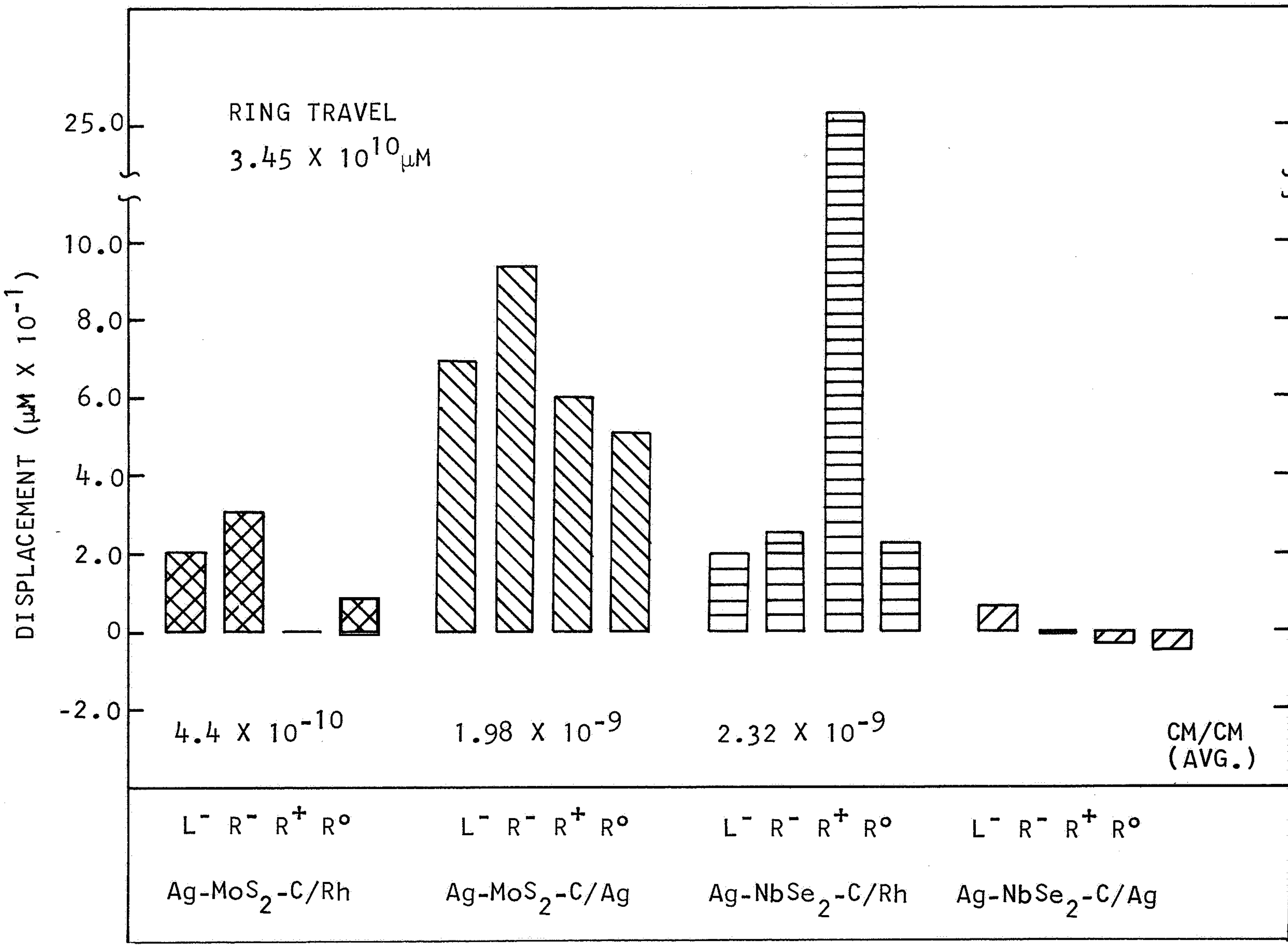


FIG. 2. NET BRUSH DISPLACEMENT DURING TWO YEARS OF VACUUM OPERATION. (Wear rates - µm of brush wear per µm of ring travel.)

TABLE 1

Statistical Analysis of the Means of the Electrical Noise Data

Parameter Analyzed	TEST PERIOD					
	0-100 Hrs.		100-4300 Hrs.		4300-18100 Hrs.	
	TEST	CL*	TEST	CL*	TEST	CL*
Electrical	$A_L < A_R$	99.9+	$A_L < A_R$	99.3	$A_R < A_L$	99.9+
Load	$B_L = B_R$		$B_L < B_R$	99.9+	$B_L < B_R$	99.9+
Differences	$C_R < C_L$	96.7	$C_R < C_L$	99.9+	$C_R < C_L$	99.9+
	$D_R < D_L$	97.6	$D_L < D_R$	99.9+	$D_L = D_R$	
Polarity	$A_R^+ < A_R^-$	99.9+	$A_R^+ < A_R^-$	99.9+	$A_R^- < A_R^+$	99.9+
Differences	$B_R^+ < B_R^-$	99.9	$B_R^- < B_R^+$	99.9+	$B_R^- < B_R^+$	99.9+
	$C_R^+ < C_R^-$	99.9	$C_R^+ < C_R^-$	99.9+	$C_R^+ < C_R^-$	99.9+
	$D_R^+ < D_R^-$	99.9	$D_R^+ < D_R^-$	99.9+	$D_R^+ < D_R^-$	99.8
Ring	$B_R < A_R$	99.9+	$A_R < B_R$	98	$A_R < B_R$	99.9+
Material	$B_L < A_L$	77.8	$B_L < A_L$	99.8+	$B_L < A_L$	99.9+
Differences	$D_R < C_R$	99.9+	$D_R < C_R$	99.9+	$D_R < C_R$	99.9+
	$D_L < C_L$	99.9+	$D_L < C_L$	99.9+	$D_L < C_L$	99.9+
Brush	$A_R < C_R$	99.9+	$A_R < C_R$	99.9+	$A_R < C_R$	99.9+
Lubricant	$A_L < C_L$	99.9+	$A_L < C_L$	99.9+	$A_L < C_L$	99.9+
Differences	$D_R < B_R$	99.9+	$B_R < D_R$	99.9+	$B_R < D_R$	99.9+
	$B_L = D_L$		$B_L < D_L$	99.9+	$B_L < D_L$	99.9+
Material	$D_R < A_R$	99.9+	$A_R < D_R$	99.9+	$A_R < D_R$	99.9+
Combination	$B_R < C_R$	99.9+	$B_R < C_R$	99.9+	$B_R < C_R$	99.9+
Differences	$D_L < A_L$	97.6	$A_L < D_L$	99.9+	$A_L < D_L$	99.9+
	$B_L < C_L$	99.9+	$B_L < C_L$	99.9+	$B_L < C_L$	99.9+

A - Ag-MoS_2-C/Rh
B - Ag-MoS_2-C/Ag
C - Ag-$NbSe_2$-C/Rh
D - Ag-$NbSe_2$-C/Ag

$\pm$ denote brush polarity.
L and R denote inductive or resistive load respectively.
*Confidence limits are for two tailed testing

consistent differences found were those related to brush lubricant and polarity. Materials Combination C had the highest noise level throughout vacuum testing.

B. Post Test Analysis

At the completion of the tests, the contacts were examined for the anomalies and modes of wear. The most obvious dissimilarity among the units was the large number of arced and burned areas on the rings of Combination C (Figure 3). This condition existed to a lesser degree on Combination D, to a limited extent on Combination B and was absent from Combination A (Table 2). In all cases the damage was greatest to the tracks that mated with anodic brushes. There were bridges[1] on the cathodic tracks, whereas the anodic tracks were generally eroded by the arcs[2] that involved mating cathodic brushes. In addition to the eroded areas and

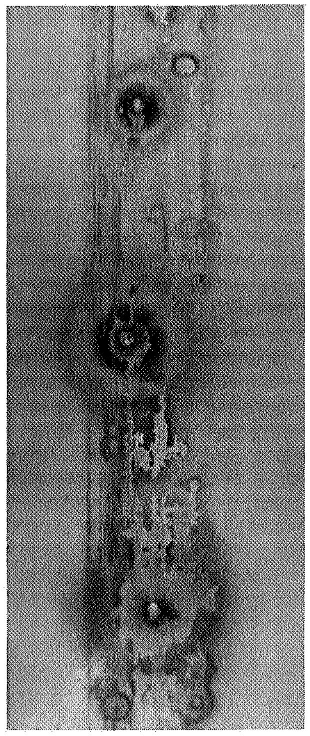
TABLE 2

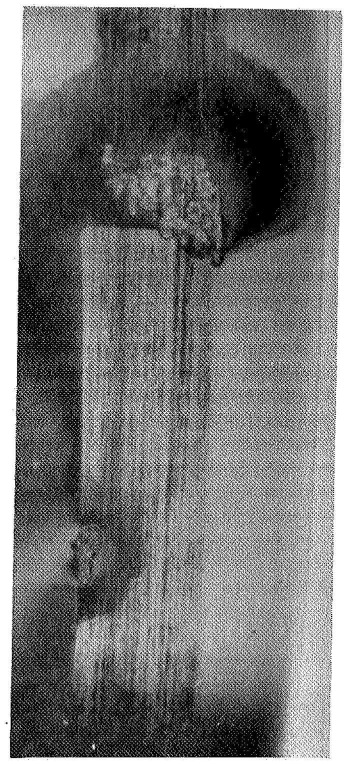
Degree of Filming and Electrical Damage on the Ring Surfaces.

PERCENT OF TRACK FILMED						TOTAL NUMBER OF DAMAGED AREAS CAUSED BY BRIDGING AND ELECTRICAL DISCHARGES			
COMBINATION	POS.	NEG.	NEUT.	IND.	RES.	POS.	NEG.	IND.	RES.
A	30	40	50	30	30	0	0	0	0
B	50	60	70	50	60	14	3	3	14
C	20	30	50	10	30	>169	>45	>99	>115
D	80	80	80	90	70	126	0	34	92

1. Bridge - Evidence of a molten metallic junction having been formed, and subsequently rupturing, between a brush and a ring.

2. Arced area - Area showing evidence of sustained erosion as if by an electrical arc.





\- Track + Track

FIGURE 3. Arc damage to ring surface.

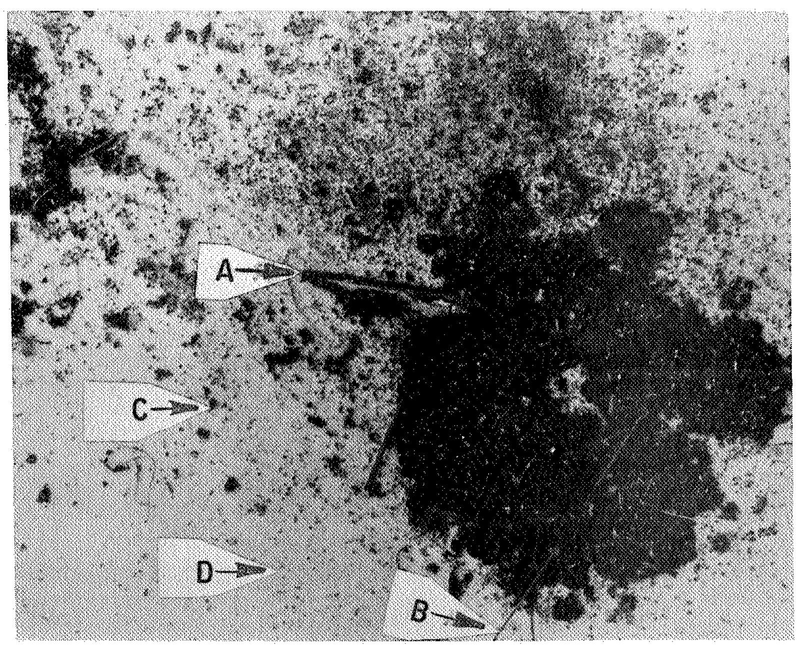


FIGURE 4: Photograph of wear debris from Combination B. (A) Brush splinter. (B) Coin silver sliver. (C) Large wear particle that could have been caused by abrasive wear. (D) Fine platelets of debris that were probably a result of adhesive wear.

deposits that were caused by the current, there were four different types of mechanical wear:

1. Adhesive wear that generated fine particles of brush material (Figures 4 and 5).
2. Abrasive brush wear caused by arc deposited material. (Figures 4, 5, 6).
3. Splintering of the brush material (Figures 4 and 7).
4. A few slivers were cut from the coin silver rings by abrasive materials in the brush faces (Figure 4).

The adhesive brush wear was the most predominant and resulted in films forming on the rings, as well as fine flakes of wear debris. The coin silver rings had a greater tendency toward film formation than the rhodium ones (Table 2). Arc deposits on the rings caused mating brushes to become grooved (Figure 5). This type of wear occurred only on the positive brushes. Both the $NbSe_2$ and MoS_2 brushes splintered to some degree, but the splintering of the MoS_2 brushes appeared to be a little greater. The difference is probably related to the fact that the $NbSe_2$ brushes were stronger (7000 psi) than the ones containing MoS_2 (5000 psi). There was only a slight amount of ring slivering and all of it appeared to be on the coin silver rings. The slivers were not of a length that would be likely to cause shorting in a system that was designed to handle normal amounts of wear debris.

In conjunction with the SEM analysis, selected regions of the contact area of the positive and negative brushes taken from a common ring were analyzed by EDAX (Table 3). The elements found on the brushes from Combinations A and B were those expected with the exception of what appeared to be trace chlorine. Traces of chlorine and silicon were found on the brushes from Combinations C and D. In addition to this, nickel and rhodium were found on the Combination C brushes. The presence of nickel and rhodium indicates material transferred from the ring, probably as a result of bridging or arcing.

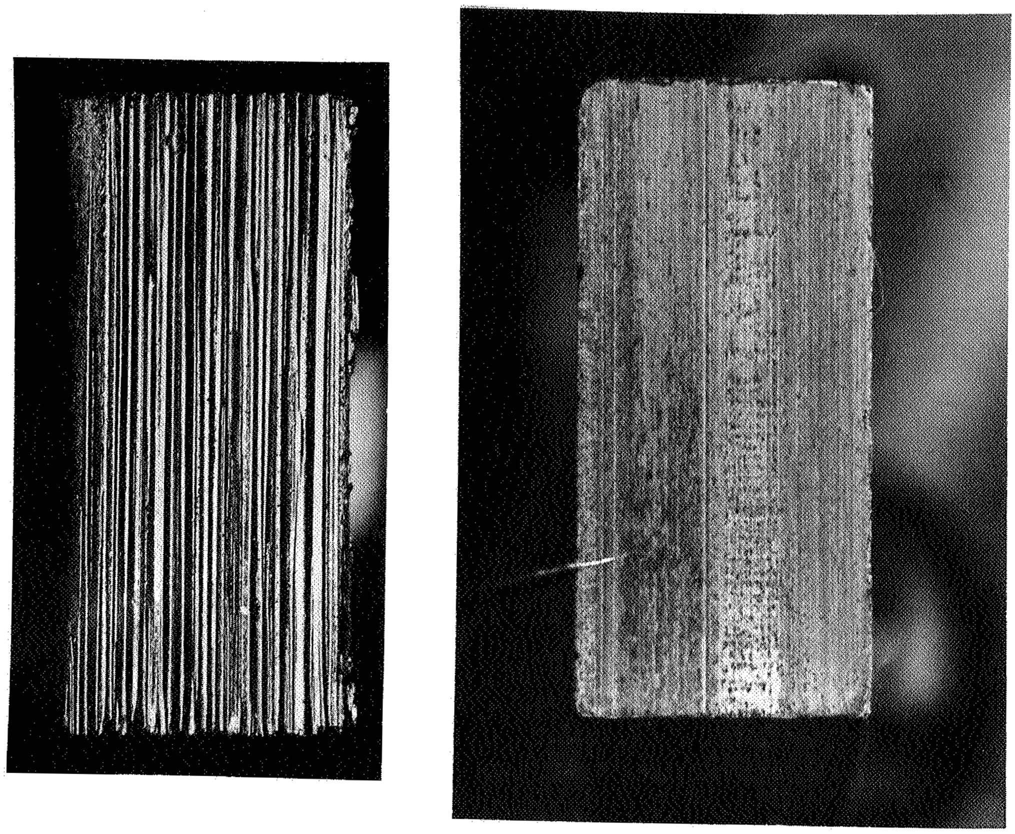


FIGURE 5: Examples of brushes undergoing abrasive and adhesive wear. The left brush face was abraded by a build-up of material on the ring surface. The right brush face was worn by adhesive wear.

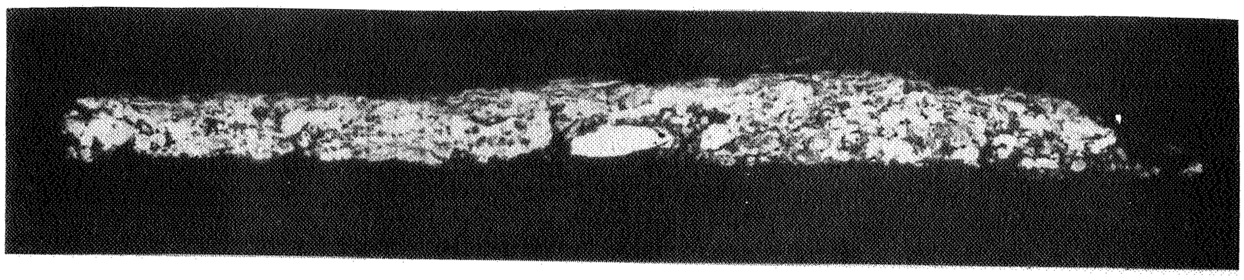


FIGURE 6: Cross section of a build-up that formed on one of the negative tracks.

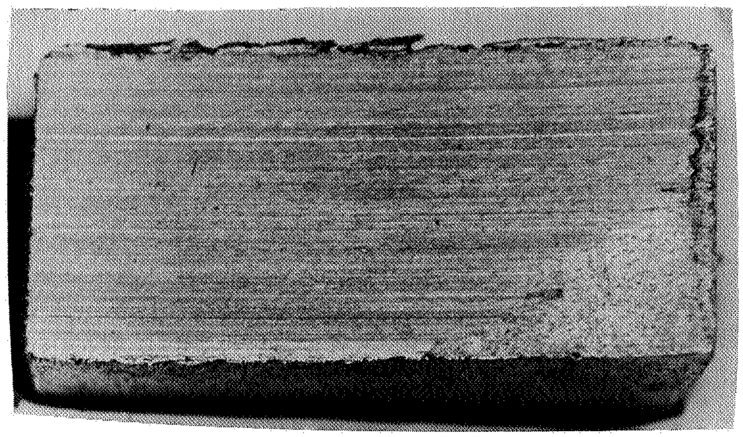


FIGURE 7: Splinter forming at the edge of a brush.

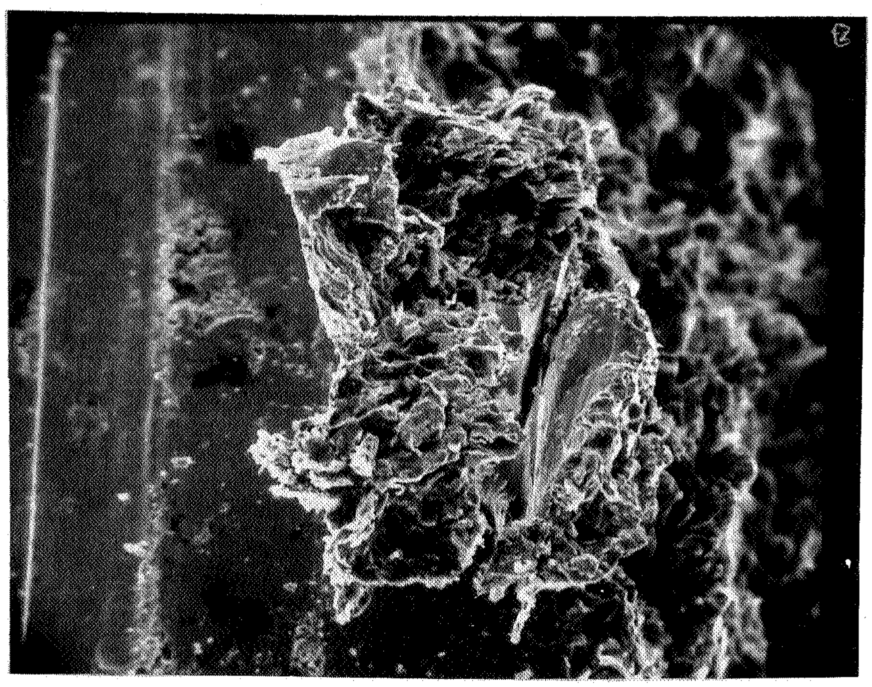


FIGURE 8: Scanning electron micrograph of a particle that was broken from a brush by splintering (original magnification 400X).

TABLE 3

Brush Analysis by EDAX

BRUSH	ELEMENTS								
	Ag	Cl	Mo	Nb	Ni	Rh	S	Se	Si
A_R^+	□	⬡	□				□		
A_R^-	□	⬡	□				□		
B_R^+	□	⬡	□				□		
B_R^-	□	⬡	□				□		
C_R^+	□	⬡		□		⬡		□	
C_R^-	□	⬡		□	⬡	⬡		□	⬡
D_R^+	□	⬡		□				□	⬡
D_R^-	□	⬡		□				□	⬡

□ Major Quantity ⬡ Trace Quantity

Since EDAX only determines the presence of an element and not its valence state, nothing can be said about the quantity of free sulfur and selenium in the brushes. MoS_2 and $NbSe_2$ are transition metal chalcogenides with layered structure[3]. These compounds consist of metal sheets sandwiched and covalently bonded between two sheets of chalcogen. These layers are in turn held together by van der Waals forces. It is well known that sulfur and selenium can exist in the free state in the respective compoundsand therefore can outgas under the proper conditions. Outgassing studies under vacuum (5×10^{-2} torr) and elevated temperature (150-200° C) have shown that the brush materials used in this study outgas free sulfur from the MoS_2 lubricated brushes and to a much greater extent free selenium from the $NbSe_2$ lubricated brushes.

The electrical characteristics of films formed between brushes and rings were examined using four probe measurements (Figure 9). The positive and negative tracks on each ring for all combinations were examined separately. At least two spots in each track were characterized. Each characterization was performed by varying the current through the brush and ring contact from 0-4 A at an approximate rate of 16 A/min. Typical current vs voltage and current vs resistance curves have been presented for each combination (Figures 10, 11, 12, and 13).

Many of the current vs voltage curves show a change in slope, i.e. resistance, in the range of 70-120 mV. Since the softening potential of silver is 90 mV it is believed that these changes are related to the softening of the Ag in the brush. Softening can bring about an increase in size and number of contact spots which results in a decrease in contact resistance (see resistance vs current curves). In some instances a constant slope occurred over the entire range of current. In these cases the film resistivity was sufficiently low that the 90 mV softening potential was never attained in the range of 0 to 4.0 A.

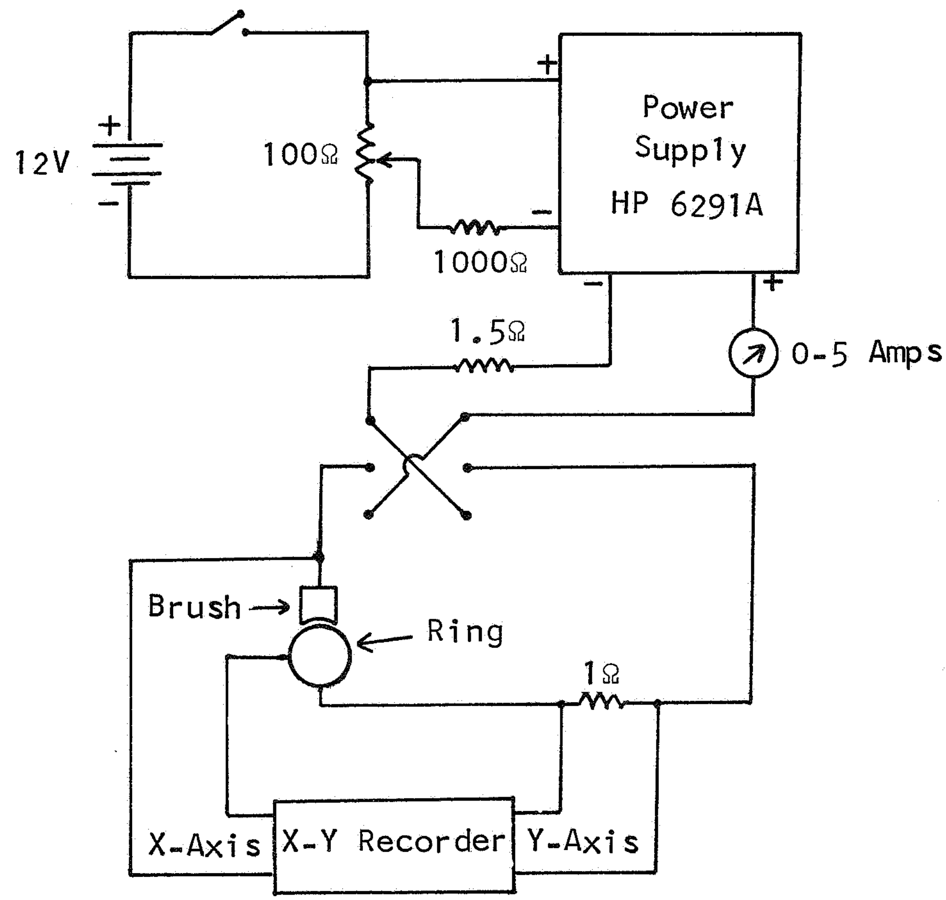


FIGURE 9. FOUR-PROBE APPARATUS FOR CHECKING CONTACT RESISTANCE

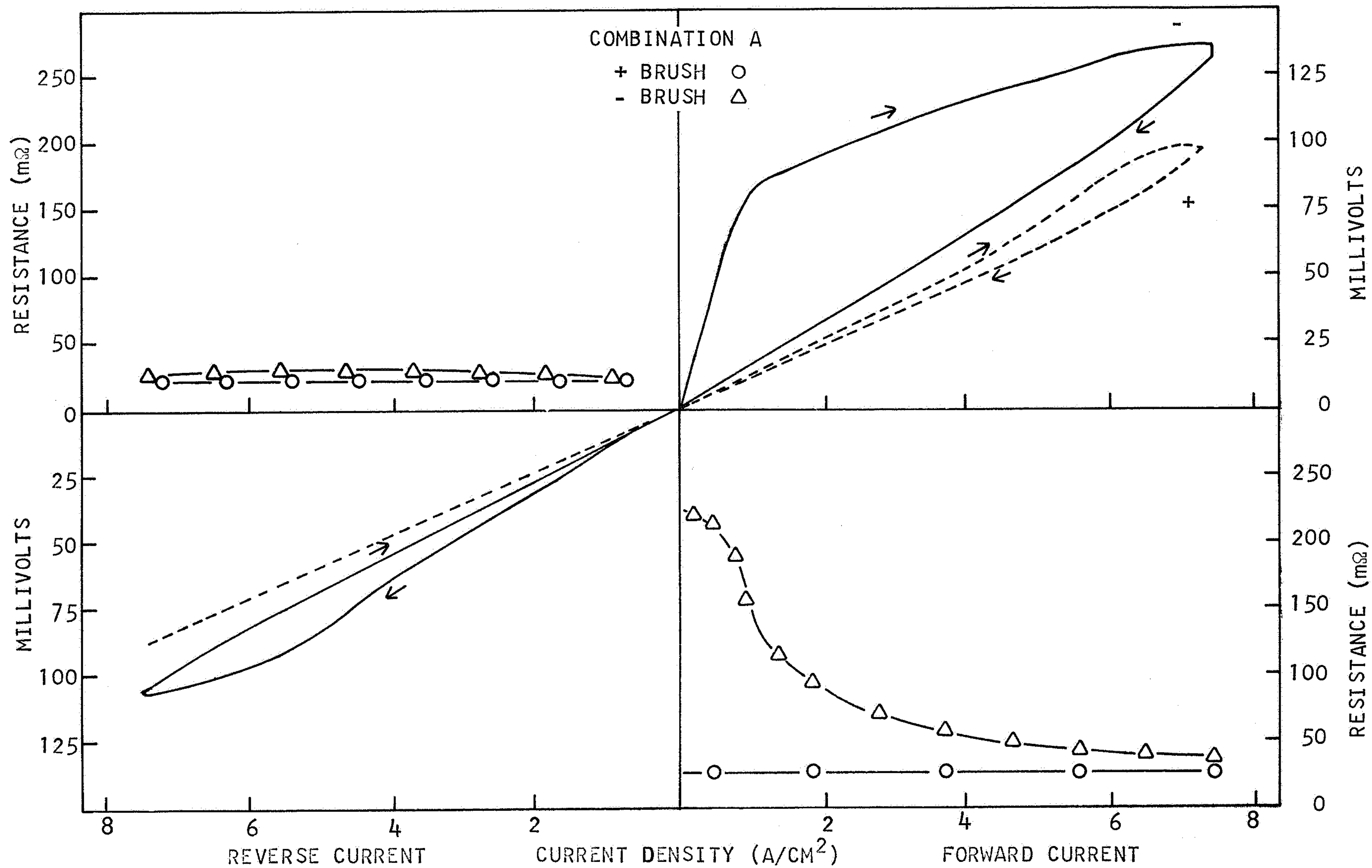


FIGURE 10. CONTACT RESISTANCE AND VOLTAGE AS A FUNCTION OF CURRENT FOR COMBINATION A. FORWARD CURRENT DIRECTION IS THAT EMPLOYED THROUGHOUT VACUUM TESTING. TEST SEQUENCE IS 0-4 AMPS IN FORWARD DIRECTION FOLLOWED BY 0-4 AMPS IN REVERSE DIRECTION.

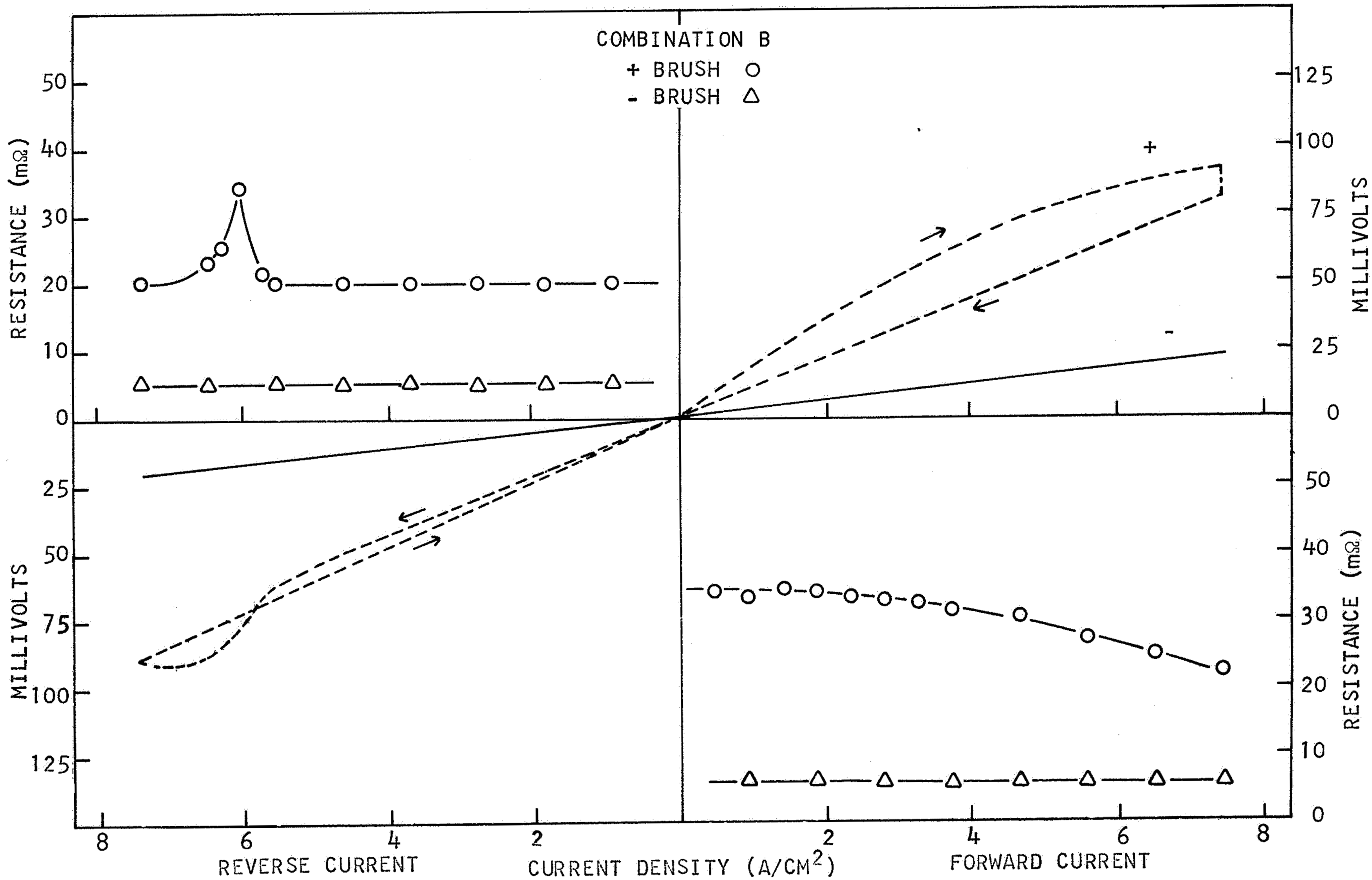


FIGURE 11. CONTACT RESISTANCE AND VOLTAGE AS A FUNCTION OF CURRENT FOR COMBINATION B. FORWARD CURRENT DIRECTION IS THAT EMPLOYED THROUGHOUT VACUUM TESTING. TEST SEQUENCE IS 0-4 AMPS IN FORWARD DIRECTION FOLLOWED BY 0-4 AMPS IN REVERSE DIRECTION.

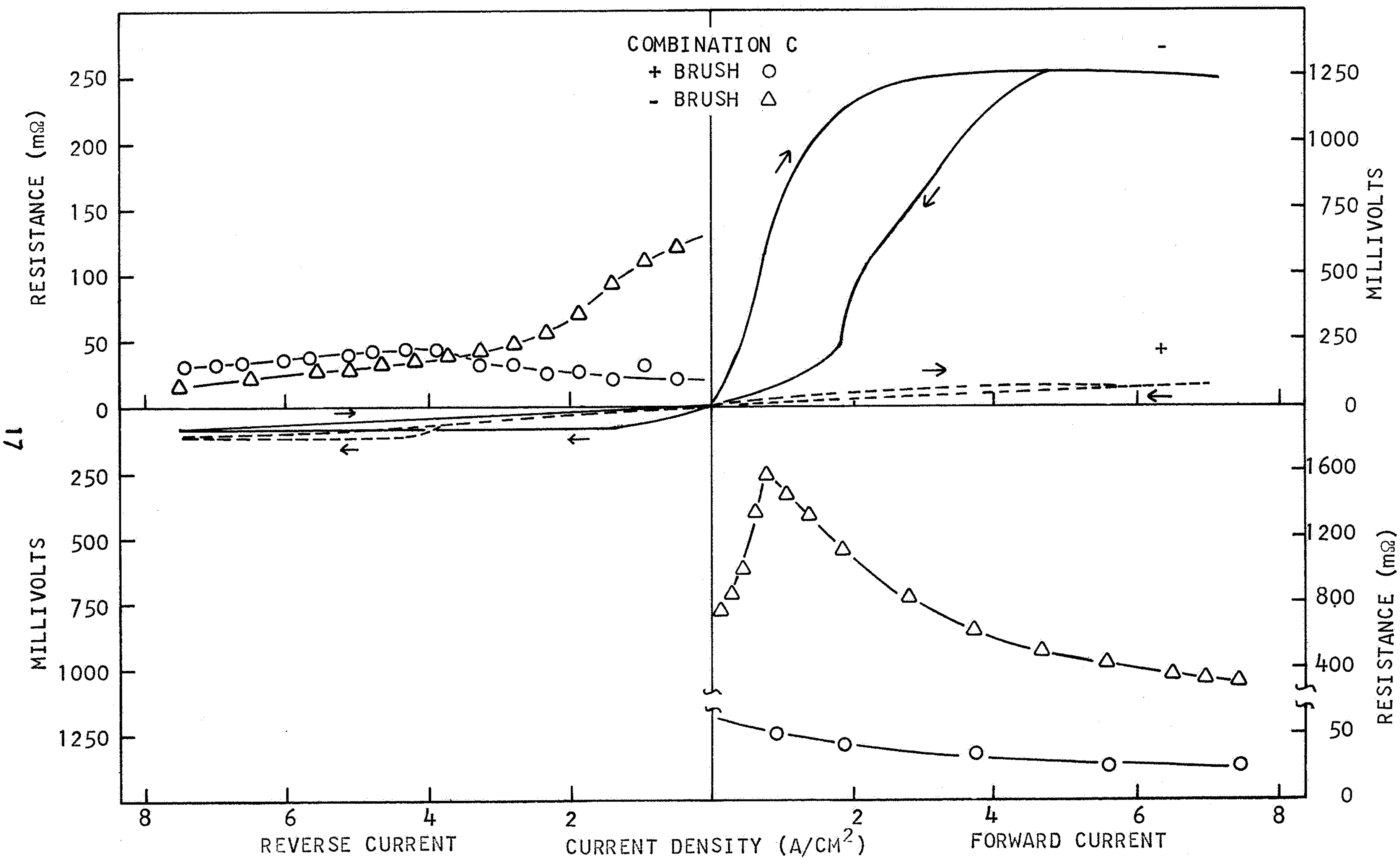


FIGURE 12. CONTACT RESISTANCE AND VOLTAGE AS A FUNCTION OF CURRENT FOR COMBINATION C. FORWARD CURRENT DIRECTION IS THAT EMPLOYED THROUGHOUT VACUUM TESTING. TEST SEQUENCE IS 0-4 AMPS IN FORWARD DIRECTION FOLLOWED BY 0-4 AMPS IN REVERSE DIRECTION.

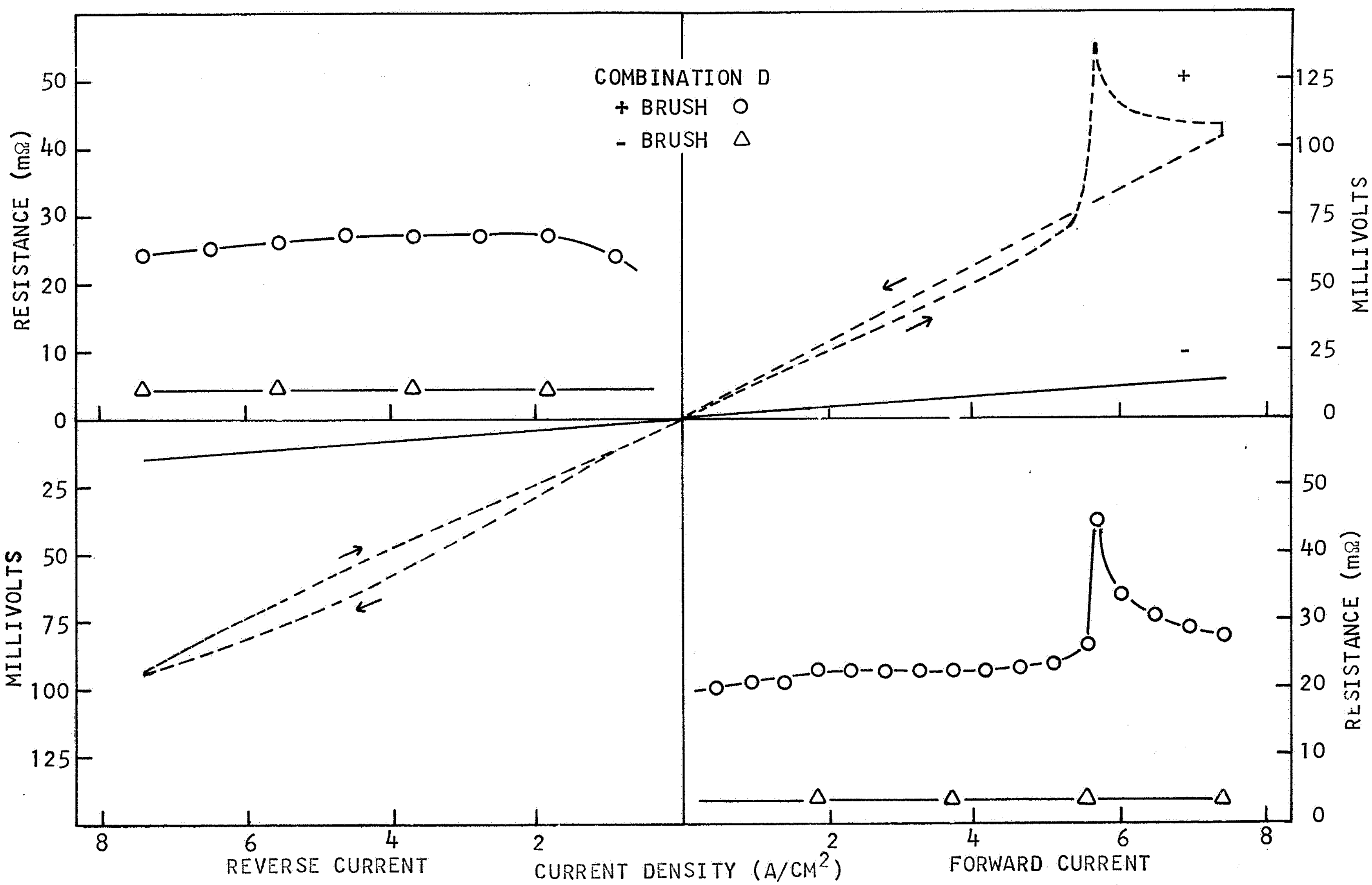


FIGURE 13. CONTACT RESISTANCE AND VOLTAGE AS A FUNCTION OF CURRENT FOR COMBINATION D. FORWARD CURRENT DIRECTION IS THAT EMPLOYED THROUGHOUT VACUUM TESTING. TEST SEQUENCE IS 0-4 AMPS IN FORWARD DIRECTION FOLLOWED BY 0-4 AMPS IN REVERSE DIRECTION.

These curves indicate that if softening occurred, the resistance in the reverse current direction was very close to the value occurring after softening for the forward direction. The one exception to this was Combination C. Contact resistance was found to be very high for the brushes with negative polarity. The resistance in the reverse current direction was found to be much less than that in the forward direction. These results indicate that a film with rectifying characteristics formed in the negative brush tracks. This effect was not found in the positive brush tracks or on other combinations.

IV. DISCUSSION

The purpose of this study was to evaluate the electrical noise, friction and wear rates of four materials combinations during periods of ambient run-in, a humidity sequence and vacuum. The fixtures and experiments were designed such that these parameters could be compared for each combination on an equal footing with time. However, during vacuum testing, problems arose such that a direct comparison cannot be made for all combinations. After 1000 hours of operation a problem with elevated temperature, which resulted in high fixture torque, developed on Combination C. It was necessary to remove power from any four of the six circuits in order to bring the fixture torque within the limitations of the mechanical feedthrough. The circuits chosen to remain in operation were those with friction and wear transducers. Friction and wear data from this combination can be compared on an equivalent footing with Combinations A and B, but electrical noise data is based on two circuits rather than six beyond 1000 hours of operation. After 7000 hours of operation (1.34×10^6 cm of ring travel) the mechanical feedthrough on Combination D developed high torque and it was necessary to stop rotation.

On the basis of friction, electrical noise, total wear, film resistivity and absence of ring damage, Combination A yielded the best performance during vacuum operation. Combination B gave equivalent performance with the exception of damage to the ring, higher total wear and higher wear rate during the last 8,000 hours of test. During the 7000 hours that Combination D was in operation, the brushes underwent very little wear and at the end of this period a low wear rate was indicated. The friction and noise levels were higher than those for Combinations A and B.

The data indicates Combination C developed more serious problems in a shorter period of time than the other three combinations. The result of the four probe analysis of this combination correlates well with the observations made during vacuum operation. The high noise levels found on the negative brushes are consistent with the high contact resistance measured between negative brushes and mating rings. The elevated temperature that developed on this fixture is most likely related to this high resistance film. It was noted that the temperature of this fixture would decrease if the current was reversed. This is consistent with the rectifying effect noted earlier (Figure 12). The large number of bridges and arced spots found on the rings could be related to the mode of breakdown of this high resistance film.

The high resistance film and rectifying effect are believed to be related to the high selenium content in the brush material. Although the same brush material was used on Combination D, the degree of ring damage and contact resistance was not as great as that found on C (Table 2 and Figures 12 and 13). This difference could be attributed to dissimilar metals used in the Combination C contacts, i.e. silver and rhodium, whereas Combination D has silver on coin silver. All that is necessary to construct a barrier rectifier is two metals with differing work functions and a thin film of insulator sandwiched between them [(4)]. In this case the two metals would be silver and rhodium and selenium or a selenium compound as the insulator. The work functions for the materials used in this study were not measured. The reported work functions as determined by contact potential, thermonic and photoelectric emission methods indicate rhodium may have the highest work function.[(5)] The direction of rectification noted in this application is consistent with rhodium having the highest work function.

V. NEW TECHNOLOGY

The system, experimental techniques and results reported to date do not directly represent a form of new technology.

VI. PROGRAM FOR NEXT REPORTING PERIOD

This is a final report.

VII. CONCLUSIONS

The data previously reported[1-2] and that generated during the last 18 months of testing along with the results of the post test analysis indicate the following:

Electrical Noise

1. Brushes lubricated with MoS_2 yielded lower noise values than those lubricated with $NbSe_2$.
2. The Ag-MoS_2-C/Rh and Ag-MoS_2-C/Ag combinations have given nearly equivalent noise performance beyond 1000 hours of vacuum operation.
3. Of the four materials combinations evaluated, low noise performance appears to be more closely related to the brush lubricant than the ring material.
4. The high noise on Combination C is related to the resistive film that formed between the negative brushes and rings.

Friction

1. There appeared to be no difference in friction coefficient for the three combinations remaining in operation at the end of the test.
2. Friction coefficients were lower in vacuum than air for MoS_2 and $NbSe_2$ lubricants.

Wear

1. The Ag-$NbSe_2$-C/Rh and Ag-MoS_2-C/Ag combinations were wearing at the highest rates of the three combinations remaining in operation.
2. The high wear rate of Ag-$NbSe_2$-C/Rh is related to bridge formation on the rings which grooved some brush faces. The excessive bridge formation and arc damage was most likely related to the high resistance film formed on this combination.
3. The Ag-MoS_2-C/Rh combination exhibited little or no wear beyond 1000 hours of vacuum operation.

4. It appears that wear rate is the result of combination performance rather than a particular ring or brush material.
5. The wear rates for the neutral brushes on all combinations were not significantly different than those brushes with positive and negative polarity.

VIII. RECOMMENDATIONS

It does not appear that a distinct choice can be made between the Ag-MoS_2-C/Rh and Ag-MoS_2-C/Ag combinations for general slip ring applications. Although the results of this study show that Combination A yielded the best overall performance, there is some reservation in recommending rhodium plated rings over coin silver rings for general use. There are problems associated with the electrodeposition of rhodium rings, such as cracked plating and trapped plating saltsand subsequent slip ring fabrication, that do not exist with coin silver rings.

The MoS_2 lubricant performed better than the $NbSe_2$. This difference has been attributed primarily to the excess selenium remaining in the $NbSe_2$ lubricated brushes after forming. Since $NbSe_2$ is classified as a conductor and MoS_2 as a semiconductor, it would appear that $NbSe_2$ would give better performance than MoS_2 in terms of electrical noise and contact resistance. Until grades of $NbSe_2$ formed to the correct stoichimetry are available for brush formation and have been evaluated, MoS_2 appears to be the best lubricant choice.